

Constraining the nuclear gluon distribution in eA processes at RHIC

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A systematic determination of the gluon distribution is of fundamental interest in understanding the parton structure of nuclei and the QCD dynamics. Currently, the behavior of this distribution at small x (high energy) is completely undefined. In this paper we analyze the possibility of constraining the nuclear effects present in xg^A using the inclusive observables which would be measured in the future electron-nucleus collider at RHIC. We demonstrate that the study of nuclear longitudinal and charm structure functions allows to estimate the magnitude of shadowing and antishadowing effects in the nuclear gluon distribution.

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Since the early days of the parton model and of the first deep inelastic scattering (DIS) experiments, determining the precise form of the gluon distribution of the nucleon has been a major goal of high energy hadron physics. Over the last 30 years enormous progress has been achieved. In particular, data from HERA allowed for a good determination of the gluon density of the proton. A much harder task has been to determine the gluon distribution of nucleons bound in a nucleus, i.e., the nuclear gluon distribution ($xg^A(x, Q^2)$). In recent years several experiments have been dedicated to high precision measurements of deep inelastic lepton scattering (DIS) off nuclei. Experiments at CERN and Fermilab focus especially on the region of small values of the Bjorken variable $x = Q^2/2M\nu$, where $Q^2 = -q^2$ is the squared four-momentum transfer, ν the energy transfer and M the nucleon mass. The data [1], taken over a wide kinematic range $10^{-5} \leq x \leq 0.1$ and $0.05 \text{ GeV}^2 \leq Q^2 \leq 100 \text{ GeV}^2$, show a systematic reduction of the nuclear structure function $F_2^A(x, Q^2)/A$ with respect to the free nucleon structure function $F_2^N(x, Q^2)$. This phenomenon is known as *nuclear shadowing effect* and is associated to the modification of the target parton distributions so that $xq^A(x, Q^2) < Axq^N(x, Q^2)$, as expected from a superposition of pp interactions (For a review see, e.g. [2, 3]). The modifications depend on the parton momentum fraction: for momentum fractions $x < 0.1$ (shadowing region) and $0.3 < x < 0.7$ (EMC region), a depletion is observed in the nuclear structure functions. These two regions are bridged by an enhancement known as antishadowing for $0.1 < x < 0.3$. The experimental data for the nuclear structure function determine the behavior of the nuclear quark distributions, while the behavior of the nuclear gluon distribution is indirectly determined using the momentum sum rule as a constraint and/or studying the $\log Q^2$ slope of the ratio $F_2^{S^n}/F_2^C$ [4]. Currently, the behavior of $xg^A(x, Q^2)$ at small x (high energy) is completely uncertain as shown in Fig. 1, where we present the ratio $R_g = xg^A/(Axg^N)$, for $A = 208$, predicted by four different groups which realize a global analysis of the nuclear experimental data using the DGLAP evolution equations [5] in order to determine the parton densities in nuclei. In particular, the magnitude of shadowing and the presence or not of the antishadowing effect is completely undefined.

In the last years the analysis of the nuclear effects in deep inelastic scattering (DIS) has been extensively discussed [6, 7] and motivated by the perspective that in a near future an experimental investigation of the nuclear shadowing at small x and $Q^2 \gg 1 \text{ GeV}^2$ using eA scattering could be performed at Brookhaven National Laboratory (eRHIC). It is expected that measurements over the extended x and Q^2 ranges, which would become possible at eRHIC, will give more information in order to discriminate between the distinct models of shadowing and the understanding of the QCD dynamics at small x . This collider is expected to have statistics high enough to allow for the determination of several inclusive and exclusive observables which are directly dependent on the behavior of the nuclear gluon distribution, as for example, the longitudinal and charm structure functions, the logarithmic slopes with respect to x and Q^2 , as well as the diffractive lepton production of vector mesons. In particular, the longitudinal structure function is expected to be measured for the first time in the kinematical regime of small x , since the electron - ion collider will be able to vary the energies of both the electron and ion beams.

In this paper we study the behavior of the nuclear longitudinal structure function F_L^A and the charm structure func-

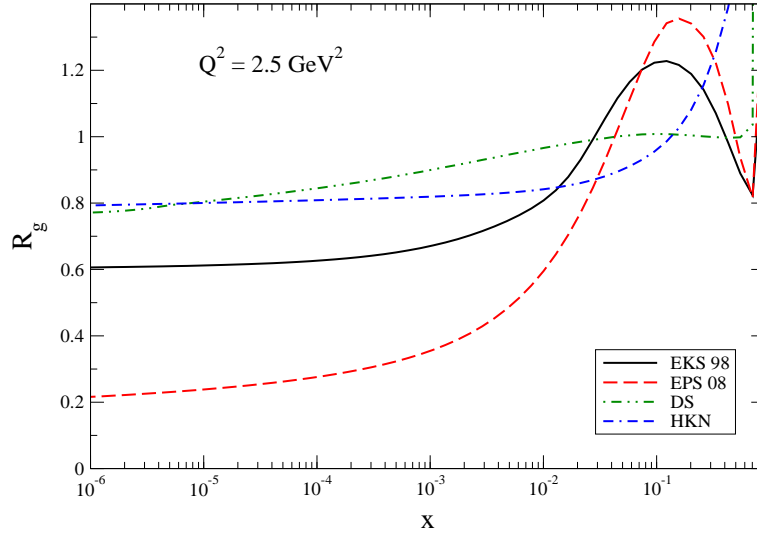


FIG. 1: Ratio $R_g = xg^A/A.xg^N$ predicted by the EKS, DS, HKN and EPS parameterizations for $A = 208$ and $Q^2 = 10 \text{ GeV}^2$.

tion $F_2^{c,A}$ and analyze the possibility to constrain the nuclear effects present in xg^A using these inclusive observables. We estimate the normalized ratios

$$R_L(x, Q^2) = \frac{F_L^A(x, Q^2)}{AF_L^p(x, Q^2)} \quad \text{and} \quad R_C(x, Q^2) = \frac{F_2^{c,A}(x, Q^2)}{AF_2^{c,p}(x, Q^2)} \quad (1)$$

considering four distinct parameterizations for the nuclear gluon distributions and compare their behavior with those predicted for the ratio $R_g = xg^A/A.xg^N$. We analyze the similarity between these ratios and demonstrate that the experimental study of these observables allow to determine the magnitude of shadowing and antishadowing effects. We calculate these observables using the Altarelli-Martinelli equation [8] and the boson-gluon fusion cross section [9], respectively. In other words, we will restrict ourselves to the descriptions which use the DGLAP evolution equations [5] to describe the behavior of the nuclear parton distributions and will assume the validity of the collinear factorization. It is important to emphasize that the theoretical understanding of small- x and large A regime of the QCD dynamics has progressed in recent years (For recent reviews see, e.g. [10]), with the main prediction being a transition of the linear regime described by the DGLAP dynamics to a nonlinear regime where the physical process of parton recombination becomes important in the parton cascade and the evolution is given by a nonlinear evolution equation. One of the main motivations for the eRHIC experiment is the study of this new regime, denoted Color Glass Condensate (CGC) [10]. As in Ref. [11] the inclusive observables at eRHIC were studied using a generalized saturation model, based on the CGC physics, the current study can be considered as complementary to that reference.

Let us start presenting a brief review of the calculations of the longitudinal and charm structure functions. The longitudinal structure function in deep inelastic scattering is one of the observables from which the gluon distribution can be unfolded. Currently, there is an expectation for new experimental HERA data for F_L taken with reduced proton energies, which will provide more direct access to the proton gluon distribution and shed light on the QCD dynamics at small- x (See, e.g. Ref. [12]). Longitudinal photons have zero helicity and can exist only virtually. In the Quark-Parton Model (QPM), helicity conservation of the electromagnetic vertex yields the Callan-Gross relation, $F_L = 0$, for scattering on quarks with spin 1/2. This does not hold when the quarks acquire transverse momenta from QCD radiation. Instead, QCD yields the Altarelli-Martinelli equation[8]

$$F_L(x, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} x^2 \int_x^1 \frac{dy}{y^3} \left[\frac{8}{3} F_2(y, Q^2) + 4 \sum_q e_q^2 \left(1 - \frac{x}{y}\right) y g(y, Q^2) \right], \quad (2)$$

expliciting the dependence of F_L on the strong coupling constant and the gluon density. At small x the second term with the gluon distribution is the dominant one. In Ref. [13] the authors have suggested that expression (2) can be reasonably approximated by $F_L(x, Q^2) \approx 0.3 \frac{4\alpha_s}{3\pi} xg(2.5x, Q^2)$, which demonstrates the close relation between the longitudinal structure function and the gluon distribution. Therefore, we expect the longitudinal structure function to be sensitive to nuclear effects. In this paper we calculate F_L using the Altarelli-Martinelli equation (2).

Let us now discuss charm production and its contribution to the structure function. In the last years, both the H1 and ZEUS collaborations have measured the charm component F_2^c of the structure function at small x and have

found it to be a large (approximately 25%) fraction of the total [14]. This is in sharp contrast to what is found at large x , where typically $F_2^c/F_2 \approx \mathcal{O}(10^{-2})$. This behavior is directly related to the growth of the gluon distribution at small- x . In order to estimate the charm contribution to the structure function we consider the formalism advocated in [15] where the charm quark is treated as a heavy quark and its contribution is given by fixed-order perturbation theory. This involves the computation of the boson-gluon fusion process. A $c\bar{c}$ pair can be created by boson-gluon fusion when the squared invariant mass of the hadronic final state is $W^2 \geq 4m_c^2$. Since $W^2 = \frac{Q^2(1-x)}{x} + M_N^2$, where M_N is the nucleon mass, the charm production can occur well below the Q^2 threshold, $Q^2 \approx 4m_c^2/x$, at small x . The charm contribution to the proton/nucleus structure function, in leading order (LO), is given by [9]

$$\frac{1}{x}F_2^c(x, Q^2, m_c^2) = 2e_c^2 \frac{\alpha_s(\mu'^2)}{2\pi} \int_{ax}^1 \frac{dy}{y} C_{g,2}^c\left(\frac{x}{y}, \frac{m_c^2}{Q^2}\right) g(y, \mu'^2), \quad (3)$$

where $a = 1 + \frac{4m_c^2}{Q^2}$ and the factorization scale μ' is assumed $\mu'^2 = 4m_c^2$. $C_{g,2}^c$ is the coefficient function given by

$$\begin{aligned} C_{g,2}^c(z, \frac{m_c^2}{Q^2}) = & \frac{1}{2} \{ [z^2 + (1-z)^2 + z(1-3z)\frac{4m_c^2}{Q^2} - z^2\frac{8m_c^4}{Q^4}] \ln \frac{1+\beta}{1-\beta} \\ & + \beta [-1 + 8z(1-z) - z(1-z)\frac{4m_c^2}{Q^2}] \}, \end{aligned} \quad (4)$$

where $\beta = 1 - \frac{4m_c^2 z}{Q^2(1-z)}$ is the velocity of one of the charm quarks in the boson-gluon center-of-mass frame. Therefore, in leading order, $\mathcal{O}(\alpha_s)$, F_2^c is directly sensitive only to the gluon density via the well-known Bethe-Heitler process $\gamma^* g \rightarrow c\bar{c}$. The dominant uncertainty in the QCD calculations arises from the uncertainty in the charm quark mass. In this paper we assume $m_c = 1.5 \text{ GeV}$.

Finally, let us briefly discuss the distinct parameterizations for the nuclear parton distributions (For details see the recent review [3]). We will make use of the existing parameterizations of the nuclear parton distribution functions based on a global fit of the nuclear data using the DGLAP evolution equations. Currently there are four parameterizations, proposed by Eskola, Kolhinen and Salgado [18], by de Florian and Sassot [19], by Hirai, S. Kumano and T. H. Nagai [20] and the very recent one proposed by K. J. Eskola, H. Paukkunen and C. A. Salgado [21]. In what follows they will be called EKS, DS, HKN and EPS, respectively. The basic idea of these approaches is that the experimental results [1] presenting nuclear shadowing effects can be described using the DGLAP evolution equations with adjusted initial parton distributions. Similarly to the global analyzes of parton distributions in the free proton, they determine the nuclear parton densities at a wide range of x and Q^2 through their perturbative DGLAP evolution by using the available experimental data from IA DIS and pA collisions as a constraint. As pointed out in Ref. [3], different approaches differ in the form of the parameterizations at the initial scale, in the use of different sets of experimental data, in the order of the DGLAP evolution, in the different nucleon parton densities used in the analysis, in the treatment of isospin effects and in the use of sum rules as additional constraints for the evolution. For instance, the DS and HKN groups provide leading (LO) and next-to-leading order (NLO) parameterizations, while EKS and EPS perform only a LO QCD global analysis. There are noticeable differences between the HKN analysis results and the ones in Ref. [19] especially in the strange-quark and gluon modifications. These differences come from various sources. First, the analysed experimental data sets are slightly different. Second, the strange-quark distributions are created by the DGLAP evolution by assuming $s(x) = 0$ at the initial Q^2 scale, and the charm distributions are neglected in Ref. [19]. These differences lead to discrepancies among the gluon modifications. In contrast to the EKS, DS and HKN parameterizations, the EPS one has included the RHIC data from [17] in the global fitting procedure. The main assumption is that these data can be understood with linear evolution. The inclusion of the high- p_T hadron data from RHIC at forward rapidities provided important further constraints for the gluon shadowing region. By construction, these parameterizations describe the current experimental data. However, the resulting parton distribution sets are very distinct. In particular, the predictions of the different groups for R_g differ largely about the magnitude of the shadowing and the presence or not of the antishadowing. It is associated to the fact that the data included in the global analyses probe the quark distribution, while the gluon is constrained only by the evolution and the momentum sum rule. As shown in Fig. 1, while the HKN and DS parameterizations predict a small value of shadowing, the EKS and EPS one predict a large amount, with the distinct predictions differing by a factor 4 at $x = 10^{-5}$. Furthermore, while the DS parameterization does not predict antishadowing and EMC effects in the nuclear gluon distribution, these effects are present in the EKS and EPS parameterizations. In the particular case of the HKN parameterization, it predicts a steep growth of the ratio R_g in the region $x \geq 10^{-1}$. It is important to emphasize that the magnitude of shadowing and antishadowing effects in the EKS and EPS parameterizations are directly related by the momentum sum rule. The large discrepancies between the predictions of the four parameterization for xg^A in all kinematical x range imply a large uncertainty in the predictions for the observables which would be measured in pA/AA collisions at LHC, for instance.

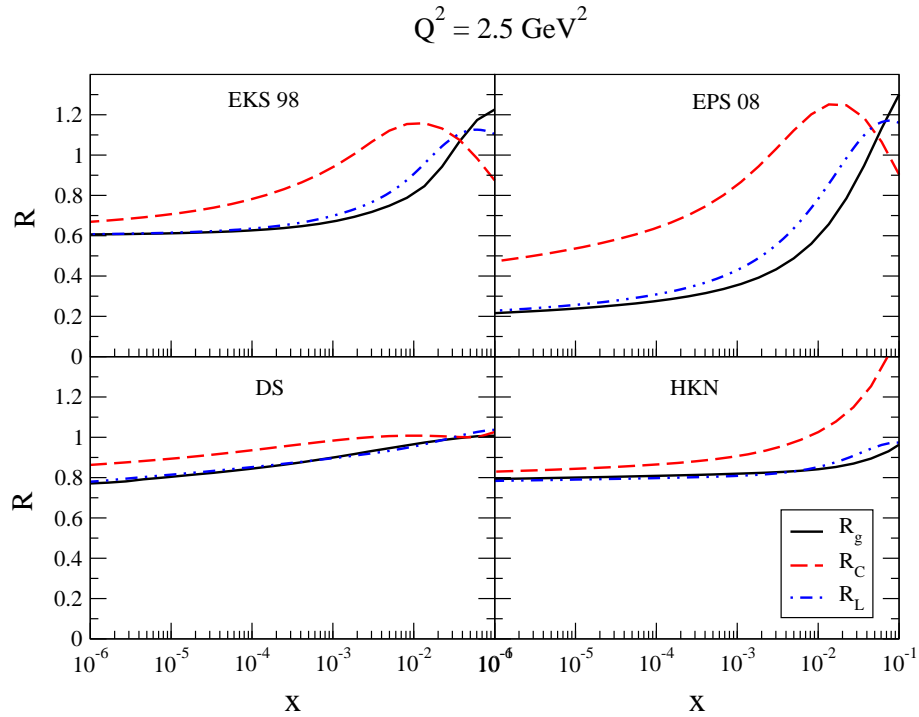


FIG. 2: Ratios R_g , R_C and R_L for the four considered nuclear parameterizations and $Q^2 = 2.5 \text{ GeV}^2$.

As mentioned above it is well known that the inclusive observables F_L and F_2^c are strongly dependent on the gluon distribution. Our goal is to quantify and determine the kinematical region where these observables directly determine the behavior of R_g . In order to obtain model independent conclusions we calculate R_L and R_C using the four parameterizations described above and compare with the corresponding predictions for R_g . As the small- x region at eRHIC will be probed at small- Q^2 we concentrate our analysis on two characteristic values of Q^2 : $Q^2 = 2.5 \text{ GeV}^2$ and 10 GeV^2 . Moreover, we only consider $A = 208$, but similar conclusions are obtained for other values of the atomic number.

In Figs. 2 and 3 we present our results. Firstly, let us discuss the small- x region, $x \leq 10^{-3}$, determined by shadowing effects. We observe that R_L practically coincides with R_g for all parameterizations and for the two values of Q^2 considered. This suggests that shadowing effects can be easily constrained at eRHIC by measuring F_L . This conclusion is, to a good extent, model independent. On the other hand, the ratio R_C gives us an upper bound for the magnitude of the shadowing effects. For example, if it is found that R_C is equal to ≈ 0.6 at $x = 10^{-4}$ and $Q^2 = 2.5 \text{ GeV}^2$ the nuclear gluon distributions from DS and HKN parameterizations are very large and should be modified. At $Q^2 = 10 \text{ GeV}^2$ the behavior of R_C is almost identical to R_g , which implies that by measuring F_2^c at this virtuality we can also constrain the shadowing effects. Considering now the kinematical range of $x > 10^{-3}$ we can analyze the correlation between the behavior of R_L and R_C and the antishadowing present or not in the nuclear gluon distribution. Similarly to observed at small values of x , the behavior of R_L is very close to the R_g one in the large- x range. In particular, the presence of antishadowing in xg^A directly implies an enhancement in F_L^A . It is almost 10% smaller in magnitude than the enhancement predicted for xg^A by the EKS and EPS parameterizations. Inversely, if we assume the nonexistence of the antishadowing in the nuclear gluon distribution at $x < 10^{-1}$, as in the DS and HKN parameterizations, no enhancement will be present in F_L^A in this kinematical region. Therefore, it suggests that also the antishadowing effects can be easily constrained at eRHIC measuring F_L . On the other hand, in this kinematical range the behavior of R_C is distinct of R_g at a same x . However, we observe that the behavior of R_C at $x = 10^{-2}$ is directly associated to R_g at $x = 10^{-1}$. In other words, the antishadowing is shifted in R_C by approximately one order of magnitude in x . For example, the large growth of R_g predicted by the HKN parameterization at $x \geq 10^{-1}$ shown in Fig. 1 implies the steep behavior of R_C at $x \geq 10^{-2}$ observed in Fig. 2. A similar conclusion can be drawn from Fig. 3. Consequently, by measuring F_2^c it is also possible to constrain the existence and magnitude of the antishadowing effects.

Some comments are in order here. Firstly, it is important to emphasize that although we have calculated F_L and F_2^c at leading order we expect that the behavior of the ratios R_L and R_C and, consequently, the main conclusions of this paper would not be strongly modified by the NLO corrections. Secondly, in our study we only have considered two

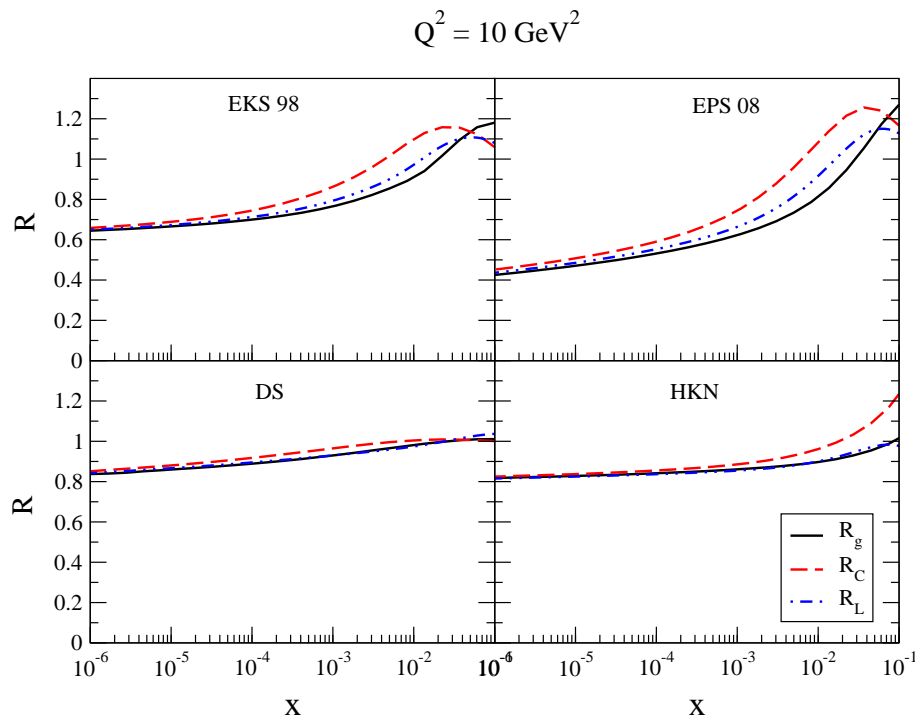


FIG. 3: The same as Fig. 2 for $Q^2 = 10 \text{ GeV}^2$.

examples of inclusive observables which would be measured at eRHIC. As demonstrated in Ref. [16] the study of the logarithmic slope of the nuclear structure function is another important quantity to probe the nuclear effects and the QCD dynamics at small- x . Furthermore, the exclusive production of vector mesons is an important complementary observable to determine the nuclear gluon distribution, since in this case the total cross section is proportional to the square of xg^A (See e.g. Ref. [22]). Finally, we have disregarded the presence of non-linear effects in the QCD dynamics and used the current parameterizations based on the DGLAP dynamics, extrapolating them to lower values of x . Consequently, our results can be regarded as conservative and serve as a baseline. Deviations from this baseline may indicate the emergence of the saturation regime of QCD.

Summarizing, our results indicate that the study of the inclusive observables F_L and F_2^c in eA process at eRHIC is ideal to constrain the nuclear effects present in the nuclear gluon distribution, which, in turn, is a crucial ingredient to estimate the cross sections of the processes which will be studied in the future accelerators. Basically, we see that by measuring these observables we will have a direct access to the nuclear gluon distribution and allow to discriminate between the different parameterizations. We hope that this paper can motivate a more accurate determination of F_L and F_2^c in the next years.

Acknowledgments

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